

Dynamics of stormflow generation—A hillslope-scale field study in east-central Pennsylvania, USA

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Abstract:

A 40 m × 20 m mowed, grass hillslope adjacent to a headwater stream within a 26-ha watershed in east-central Pennsylvania, USA, was instrumented to identify and map the extent and dynamics of surface saturation (areas with the water table at the surface) and surface runoff source areas. Rainfall, stream flow and surface runoff from the hillslope were recorded at 5-min intervals from 11 August to 22 November 1998, and 13 April to 12 November 1999. The dynamics of the water table (0 to 45 cm depth from the soil surface) and the occurrence of surface runoff source areas across the hillslope were recorded using specially designed subsurface saturation and surface runoff sensors, respectively. Detailed data analyses for two rainfall events that occurred in August (57.7 mm in 150 min) and September (83.6 mm in 1265 min) 1999, illustrated the spatial and temporal dynamics of surface saturation and surface runoff source areas. Temporal data analyses showed the necessity to measure the hillslope dynamics at time intervals comparable to that of rainfall measurements. Both infiltration excess surface runoff (runoff caused when rainfall intensity exceeds soil infiltration capacity) and saturation excess surface runoff (runoff caused when soil moisture storage capacity is exceeded) source areas were recorded during these rainfall events. The August rainfall event was primarily an infiltration excess surface runoff event, whereas the September rainfall event produced both infiltration excess and saturation excess surface runoff. Occurrence and disappearance of infiltration excess surface runoff source areas during the rainfall events appeared scattered across the hillslope. Analysis of surface saturation and surface runoff data showed that not all surface saturation areas produced surface runoff that reached the stream. Emergence of subsurface flow to the surface during the post-rainfall periods appeared to be a major flow process dominating the hillslope after the August rainfall event. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS Hillslope dynamics; surface saturation areas; surface runoff source areas; saturation excess surface runoff; infiltration excess surface runoff; subsurface saturation sensors; surface runoff sensors; variable source area

INTRODUCTION

Hydrologic processes within a watershed are spatially and temporally dynamic. During and immediately after rainfall events, these dynamics are pronounced. Rapid changes in soil moisture cause appearance and disappearance, or expansion and contraction, of surface saturation areas (SSAs; areas with the water table at the surface) and surface runoff source areas (SRSs). Tischendorf (1969, from Chorley, 1978) defined these dynamic source areas of stormflow as 'areas that are pulsating, shrinking and expanding, in response to rainfall.' Zollweg *et al.* (1995) termed these dynamic source areas as 'critical source areas', stating that they contribute disproportionately to overall watershed response.

The SRSs occur when rainfall rate exceeds soil infiltration rate (infiltration excess (IE) surface runoff), or when the soil storage capacity is exceeded (saturation excess (SE) surface runoff). The nature of occurrence of surface runoff varies depending on watershed conditions and rainfall characteristics. The sources are different

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for IE and SE surface runoff processes. The majority of flow from the IE surface runoff comes from rainfall, whereas SE surface runoff includes both rainfall and subsurface (groundwater and soilwater) contributions. The occurrence of IE surface runoff is limited to the rainfall periods, whereas SE surface runoff can occur during and immediately after rainfall events. The ability to identify and delineate various SRSs and the knowledge of the dynamics of surface runoff generation processes during and after rainfall events are significant additions to our basic understanding of watershed hydrology. The differentiation of surface runoff generation processes is very important from a water quality standpoint, because nutrient concentrations of groundwater and soilwater may differ from rainfall. Also, the knowledge of occurrence and dynamics of SE and IE surface runoff will help hydrologists to better understand and model the basic hydrological concepts pertaining to nutrient and sediment transport to the surface waters.

Knowledge of source areas of stormflow and their dynamics is critical for water quality management. 'The transport of fertilizers, herbicides, or animal wastes, for example, can be highly dependent upon where the material is placed in relation to the runoff source areas' (Betson and Ardis, 1978, p. 308). Kunkle (1970, from Betson and Ardis, 1978), from a study in Vermont, USA, concluded that 'because of the runoff processes involved, upland contributions of bacteria to streams were small compared to contributions from land surfaces near channels, the channel itself, or direct inputs.' Using a variable source-area model, Zollweg *et al.* (1995) demonstrated that a land-use change on a critical SRS, comprising 1% of the total watershed area, could reduce dissolved phosphorus exports to surface waters by 24%.

Areas of surface saturation act as source areas of surface runoff (Ward, 1984). O'Laughlin (1981) derived criteria for the existence of SSAs. Beven and Kirkby (1979) presented a variable source-area model, the TOPMODEL, to identify the occurrence of SSAs at a basin scale. All the field studies focused at characterizing partial participation of watersheds recorded either the occurrence of SRSs (e.g. Gburek and Zollweg, in press) or SSAs (e.g. Anderson and Burt, 1978) and tried to relate one to the other. The underlying assumption was that SSAs produce surface runoff on further addition of rainfall. None of the field studies independently recorded the occurrence of SSAs and SRSs to validate the above assumption. For the purpose of realistic representation of partial participation of watersheds in stormflow generation, it is important to validate this assumption. The relationship between the SSAs and SRSs can be derived from independent field measurements.

Several field studies (e.g. Hewlett, 1961; Dunne and Black, 1970a,b) have shown that stormflow source areas usually do not occur over the entire watershed. Freeze (1974) concluded that storm hydrographs originate from small, but consistent, portions of upstream source areas that constitute no more than 10%, and usually 1–3%, of the basin area. Rawitz *et al.* (1970) concluded that the source areas, as defined by the storage volume in the soil, appear to be more important than the total watershed areas. Hewlett (1961) observed that these source areas of stormflow often were adjacent to the streams. Other field studies, however, identified source areas both near to and far from streams and distributed across the watersheds. Amerman (1965) observed that because of varying moisture potentials among watershed soils, source areas were located in seemingly random fashion on ridge tops, valley slopes and valley bottoms, producing stormflow through surface and subsurface flow processes. Jones (1979) also observed the formation of disjunct SSAs during rainfall events. Ward (1984) noted that SSAs may occur widely distributed within a watershed and often in locations far removed from stream channels. He concluded that if these disjunct SSAs have effective hydrological connections to the stream or to other saturated areas that are connected to the stream, they may contribute to stormflow.

There have been a number of attempts to map SSAs and SRSs in field situations. Rogowski *et al.* (1974) compared streamflow response to rainfall events using soil moisture potential data collected every 48 h via manual tensiometers. Anderson and Burt (1978) attempted to map the variable stormflow source areas with hourly soil moisture potential data collected using multiple automated tensiometers. These two studies recorded soil moisture potential at pre-set depths in the soil and made the assumption that zero available soil moisture storage leads to SSAs that produce surface runoff. This assumption is valid for SE surface runoff but not for IE surface runoff. When IE surface runoff occurs, soil saturation occurs only at the surface and not over the entire soil profile.

Recently, Gburek and Zollweg (in press) conducted a runoff field study in a small headwater watershed (the Brown Watershed) in east-central Pennsylvania, USA, using specially designed saturation detectors. These saturation detectors, designed by Zollweg (1996), recorded the maximum spatial extent of SSAs that occurred during rainfall events. However, these detectors offered no information on the spatial and temporal dynamics of SSAs during and after rainfall events, the water table status, or the type of runoff that occurred.

STUDY OBJECTIVES AND HYPOTHESES

The goal of the hillslope-scale study described in this paper was to demonstrate the necessity and the ability to record the spatial and temporal dynamics of SSAs and SRSs, independently, during and after rainfall events. For this study, the hillslope dynamics data were recorded at 5-min intervals, the same as rainfall and streamflow measurements. The approach described in this paper combines, refines and extends the efforts by Rogowski *et al.* (1974), Anderson and Burt (1978) and Gburek and Zollweg (in press), who attempted similar measurement schemes. Subsurface saturation (SS) and surface runoff (SR) sensors designed by Srinivasan *et al.* (2000) were used to record the dynamics and extents of SSAs and SRSs. This paper presents quantitative data relative to hillslope dynamics to test the following three hypotheses:

1. during rainfall events, both IE and SE surface runoff occur;
2. not all SSAs produce surface runoff;
3. water table dynamics and the occurrence of SRSs must be measured at the same time intervals as the rainfall measurements in order to capture the overall watershed dynamics.

SITE DESCRIPTION AND INSTRUMENTATION

This SSA–SRS identification and mapping study was conducted in the Brown Watershed (26 ha) in the Ridge and Valley region of east-central Pennsylvania, USA (Figure 1). The climate is temperate and humid, average precipitation is approximately 1090 mm/year, and stream flow is about 460 mm/year (Gburek and Zollweg, in press). Cropland covers 97% of the watershed, with the remaining 3% in forest land-use. The runoff study site located within the Brown Watershed was a 40 m × 20 m hillslope adjacent to a headwater stream. The study site is on Berks soil, which is loamy, moderately deep and well drained; the depth to shale bedrock is 50 to 100 cm (USDA, 1985). The 40 m × 20 m hillslope was covered with grass, which was unfertilized but mowed periodically to a height of less than 10 cm. The hillslope had been in continuous grass at least for the last 15 years.

Figure 2 shows the location of instruments at the study site. Approximately 2.16 ha of the watershed drained between the upper and lower flumes. The four lateral runoff flumes measured the surface runoff from the study site. V-shaped dikes made by placing soil berms at the lower boundary of the hillslope directed the surface runoff from the study site to pass through one of the four lateral runoff flumes. The 5-m-wide riparian zone between the stream channel and the lateral runoff flumes remained moist for most of the year as a result of subsurface flow contributions (Gburek and Zollweg, in press). A spring downstream from the study site hillslope that feeds the lower flume was also monitored by a separate flume. During dry periods, the majority of flow to the stream came from subsurface contributions feeding this spring.

A tipping bucket rain gauge measured the rainfall intensity at 5-min intervals. Four shallow wells, installed across the hillslope, measured the depths to water table to a depth of 1.8 m below land surface. The upper flume in the stream measured the flow entering the hillslope segment, and the lower flume measured the flow leaving the hillslope segment. Details on the construction and installation of the SS and SR sensors can be found in Srinivasan *et al.* (2000). Figure 3 shows the photographs of these two sensors. Briefly, the SS sensor was a 2-mm-thick printed circuit board with six sensor pins to record the water table at six different depths. When installed in the field, the sensor pins were set at 5, 10, 20, 30 and 45 cm below the soil surface and at

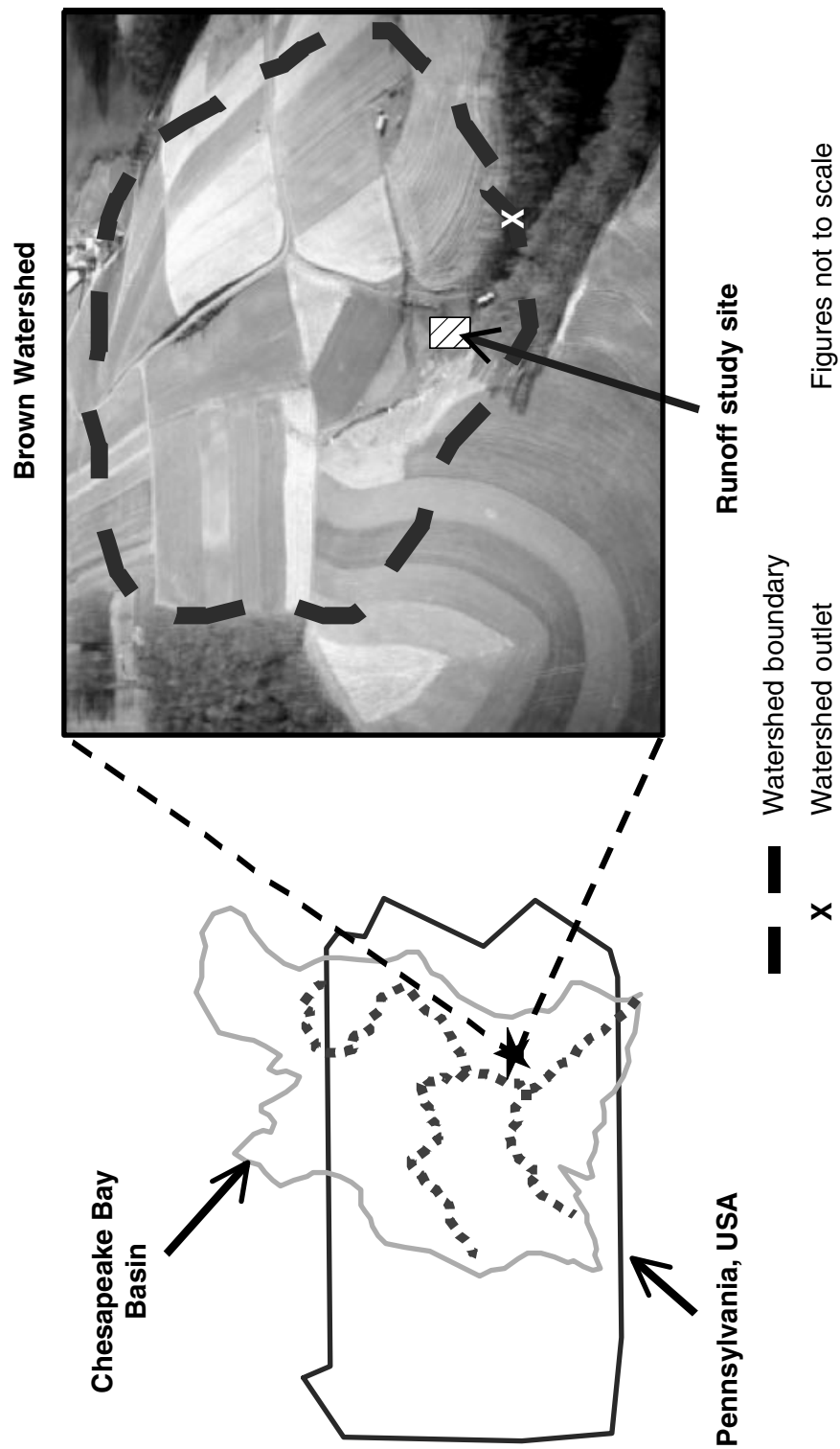


Figure 1. Location of the Brown Watershed and the runoff study site

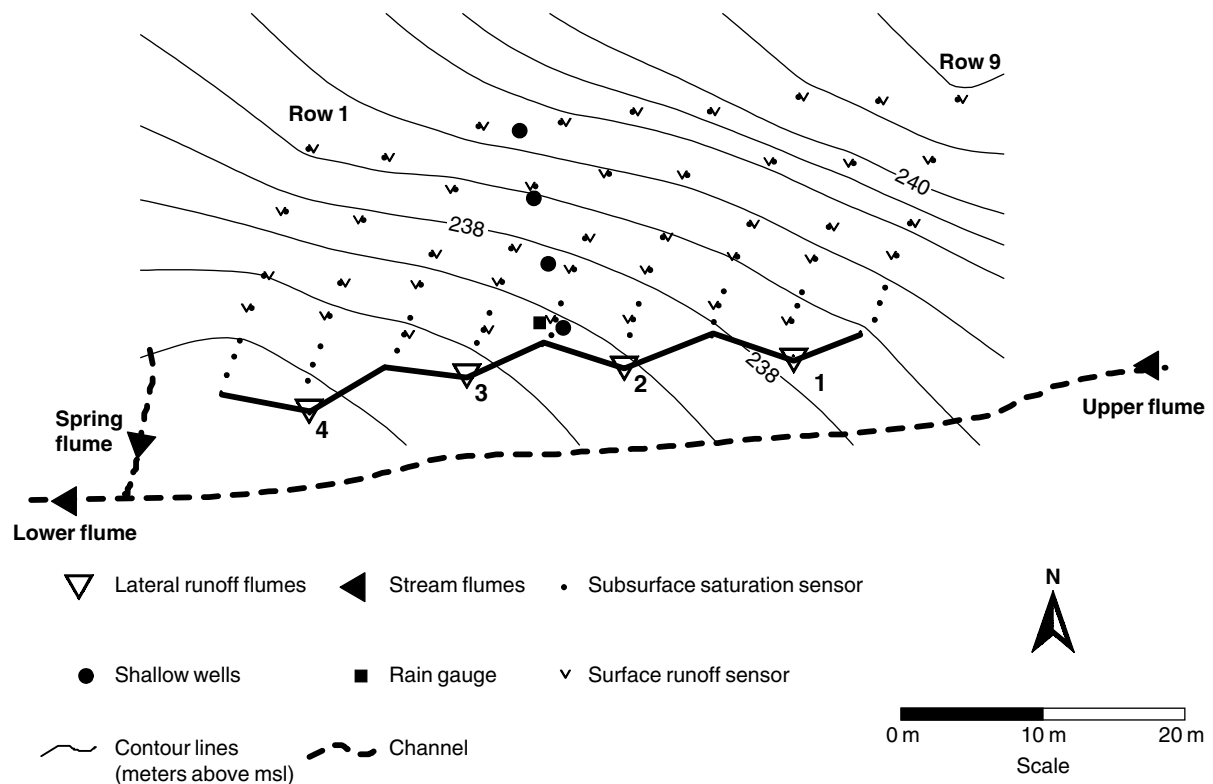
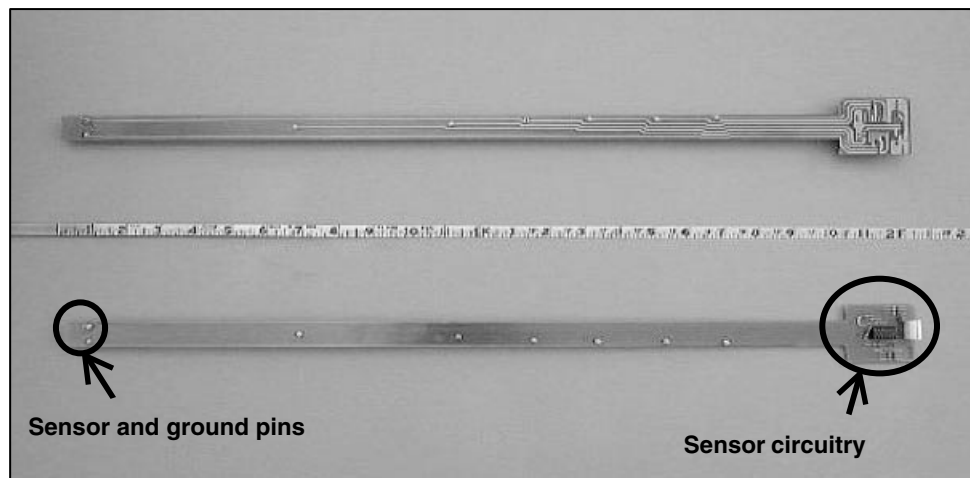


Figure 2. Instrumentation in the Brown Watershed study site

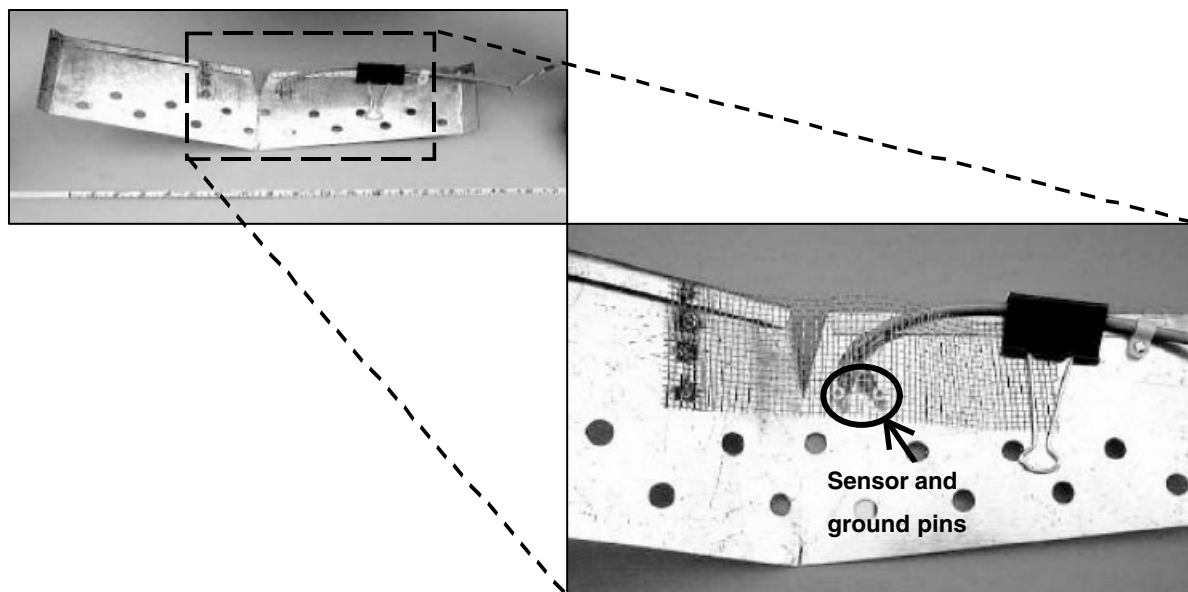
the soil surface. The sensor was installed, centered vertically, inside a 5-cm diameter access tube. The bottom end of the tube was sealed to prevent the entry of insects, and the sides were finely slotted to allow lateral flow of water into the tube. Small drainage holes were drilled at the bottom of the tube. An expanded cap assembly covered the top of the tube preventing the direct entry of rainwater into the tube. The net cost of this sensor was approximately US \$20, excluding the tube assembly.

The SR sensor, a miniature V-notch weir made of 2-mm-thick galvanized sheet metal, recorded the timing and occurrence of surface runoff. The sheet was bent upslope on either side of the centre to route the runoff water through the V-notch. A sensor pin and a ground pin set 2 cm apart and 3 cm away from the V-notch, and aligned with the bottom of the V-notch, were located on the upslope side of the sensor. The bottom of the V-notch was placed just at the soil surface to allow continuous flow without ponding. Two rows of holes, 1.5 cm diameter each, were punched and staggered on the bottom portion of the weir. When the sensor was installed in the field, these holes remained below the soil surface; thereby preventing the weir from blocking shallow subsurface flow, causing it to move upward and influence the surface flow. Wire mesh around the pins and the V-notch prevented the deposition of debris on the pins and blocking of flow through the V-notch. When there was flow through the V-notch, water bridged the sensor and ground pins and a unique voltage signal was emitted to the data logger. At other times, a zero volt signal was emitted. The net cost of the SR sensor was approximately US \$15 each. The SR sensor was intended only to record the occurrence of surface runoff, and the size of the upstream drainage area was not an important consideration.

Sixty-three SS and 42 SR sensors connected to data loggers were installed within the study site. The SS sensors were placed in nine rows perpendicular with respect to the hillslope contours (Figure 2). The rows were spaced at 5-m intervals and each row had seven SS sensors. The three downhill SS sensors in each row



(a)



(b)

Figure 3. (a) Subsurface saturation sensor—front and rear views; (b) Surface runoff sensor (Srinivasan *et al.*, 2000). Reproduced by permission of ASAE

were placed at 1-m interval spacing. Subsequent upslope sensors were set at 2 and 4 m intervals as shown in Figure 2.

Forty-two SS sensors were paired with SR sensors. Adjacent downstream SR sensors were installed on the alternate sides of the SS sensors to prevent channel flow from occurring. For the 21 unpaired SS sensors, flows through the lateral runoff flumes were used to record the occurrence of surface runoff. Sensors further from the stream were paired to record the occurrence of disjunct SSAs and SRSs. Each paired sensor was assumed to represent the same spatial location, allowing the data from these paired sensors to be combined

spatially. By combining the data from the paired sensors, the interaction between the water table and SRSs could be mapped and characterized over space and time. When a SS sensor detected the water table at the soil surface, the entire soil profile was assumed to be saturated. When a SS sensor recorded the water table at the surface and the paired SR sensor recorded surface runoff at the same time, the runoff was considered SE surface runoff. When a SS sensor did not record the water table at the surface and the paired SR sensor recorded surface runoff at the same time, it was IE surface runoff.

Data from SS and SR sensors were interpolated using the 'kriging' and 'nearest neighbourhood' techniques, respectively, within the SURFER (Golden Software, 1999) contouring and gridding software. Because of the spatial discontinuity associated with the surface runoff data, the nearest neighbourhood technique was used to interpolate the data from SR sensors. When all 63 SS sensors recorded the water table at the surface, the total extent of the SSA (within the study site) was calculated to be approximately 675 m². Similarly, when all 42 SR sensors recorded surface runoff, the total area producing surface runoff (within the study site) was calculated to be approximately 630 m².

DATA COLLECTION AND ANALYSES

Rainfall, stream flow, watertable status and occurrence of surface runoff data were collected from 11 August to 22 November 1998, and 13 April to 12 November 1999. During 1998 and between April and July 1999, dry weather conditions persisted throughout the north-eastern USA. Fifteen rainfall events ranging from 4.6 to 36.3 mm occurred during these dry periods producing a total of 116 mm of rainfall. The upper and spring flumes, and the four lateral runoff flumes did not record any flow during these dry periods. For most of the rainfall events, stormflow measured by the lower flume came from direct channel precipitation and from the 5-m-wide riparian zone. Between August and November 1999, sixteen rainfall events produced a total of 415 mm of rainfall. Many of these rainfall events produced increasing flows through the stream and spring flumes. The hillslope dynamics of two randomly selected rainfall events that occurred during this period are discussed in detail in this paper.

RESULTS AND DISCUSSION

The first rainfall event in discussion occurred during 26 and 27 August 1999 (hereafter referred to as rainfall event 1) and the second rainfall event occurred on 16 September 1999 (rainfall event 2). The pre-storm baseflow conditions, rainfall characteristics and flow rates for rainfall events 1 and 2 are listed in Table I. Rainfall event 1 was a high-intensity, short-duration rainfall event as compared with rainfall event 2. Low flow conditions before rainfall events 1 and 2 showed the dry conditions that existed in the watershed. Figures 4 and 5 depict the rainfall and flow conditions for the periods before, during and after rainfall events 1 and 2, respectively. Figures 6 and 7 illustrate the spatial and temporal dynamics of the water table, SSAs and SRSs before, during and after rainfall events 1 and 2, respectively. After rainfall event 2, the lower flume was malfunctioning between 2125 h on 16 September and 0955 hours on September 17 and was reset at 1000 hours (Figure 5).

Infiltration excess versus saturation excess surface runoff areas

Analysis of data from SS and SR sensors showed that both IE and SE surface runoff occurred during rainfall events 1 and 2. It is difficult to assess the significance of disjunct IE surface runoff areas without knowing the flow rates and volumes of surface runoff from these areas. If these IE surface runoff areas are hydrologically connected to other SSAs, their contributions to the overall stormflow become significant.

On 26 August 1999, at 2215 hours (Figure 6b), 35 min after the start of rainfall event 1, 26.2 mm of rain had fallen, the extent of SRS was 240 m², but there was no trace of SSAs. At 2215 hours, the ratio of IE

Table I. Summary of rainfall and flow conditions for rainfall events 1 and 2

	Rainfall event 1 (26 and 27 August 1999)	Rainfall event 2 (16 September 1999)
1. Pre-storm baseflow rates ($\times 10^{-5}$ m ³ /s)		
a. Upper flume	0.0	2.3
b. Spring flume	0.5	15.2
c. Lower flume	5.0	1.4
2. Rainfall characteristics		
a. Amount (mm)	57.7	83.6
b. Duration (min)	150	1265
c. Maximum intensity (mm/h)	23.1	4.0
3. Peakflow rates ($\times 10^{-5}$ m ³ /s)		
a. Upper flume	441.0	648.0
b. Spring flume	218.0	1185.0
c. Lower flume	795.0	1940.0

surface runoff areas to the total SRSs recorded across the hillslope was as large as one. Total SRS is the summation of IE and SE surface runoff source areas. However, none of the four lateral runoff flumes recorded surface runoff from the hillslope until 2240 hours (this was 60 min after the rainfall event had begun; and a total of 47 mm of rain had fallen by 2240 hours). Evidently, surface runoff from the IE areas did not reach any of the four lateral runoff flumes until 2240 hours. Runoff from these IE surface runoff areas could have infiltrated into the soil. At 2340 hours (Figure 6c), the extents of SRSs and SSAs (570 and 105 m², respectively) were the maximum for rainfall event 1. At this time, SS sensors adjacent to the lateral runoff flumes 1, 2 and 3 recorded the water table at the surface, but none of those lateral flumes recorded surface runoff (Figures 4 and 6). This could be an indication that subsurface flow paths transmitted the excess moisture to the stream. None of the SS sensors adjacent to lateral runoff flume 4 recorded the water table at the soil surface (Figure 6c), but that particular flume did record surface runoff of 2.8×10^{-5} and 0.5×10^{-5} m³/s at 2340 and 2345 hours, respectively. The flows recorded by the lateral runoff flume 4 must have been IE surface runoff as no SSAs were recorded near that lateral flume during the entire rainfall event.

A 2 h and 15 min period on 16 September (from 1410 to 1625 hours) during rainfall event 2 was selected to demonstrate the dynamics (appearance and disappearance) of SSAs and SRSs (Figure 7). During this period, 15 mm of rain fell, and the extent of IE surface runoff areas fluctuated between 10 m² (1430 hours) and 80 m² (1515 hours). From 1410 to 1625 hours, the extent of SSAs increased from 208 to 230 m². At 1625 hours, the extent of SSAs recorded was the maximum (230 m²) for rainfall event 2. Areas on the western side of the hillslope that initially were recording IE surface runoff started to record SE surface runoff as the water table reached the surface (contrast Figure 7a and d). A portion of the hillslope that was recording IE surface runoff at 1410 hours was no longer recording any surface runoff at 1455, 1540 and 1625 hours (compare Figure 7a with 7b, c and d). Areas that did not record any surface runoff at 1410 and 1455 hours recorded IE surface runoff at 1540 and 1625 hours (compare Figure 7a and b with 7c and d).

Dynamics of infiltration excess surface runoff areas

During rainfall event 1, the occurrence of IE surface runoff source areas did not appear to be related to the occurrence of SSAs (Figure 6). Between 2340 (August 26) and 0025 hours (August 27), only 1.1 mm of rainfall was recorded and SSAs and SRSs began to diminish in size. At 2340 hours, the extent of SRS (IE) was 570 m² (Figure 6c). At 2355 hours (not shown in Figure 6), the extent of SRSs (IE) was 55 m². This shows the highly transient nature of IE surface runoff areas.

As the rainfall intensity varied during both rainfall events 1 and 2, the extent of IE surface runoff areas changed. These changes in SRSs were more pronounced during rainfall event 1 than during rainfall event 2

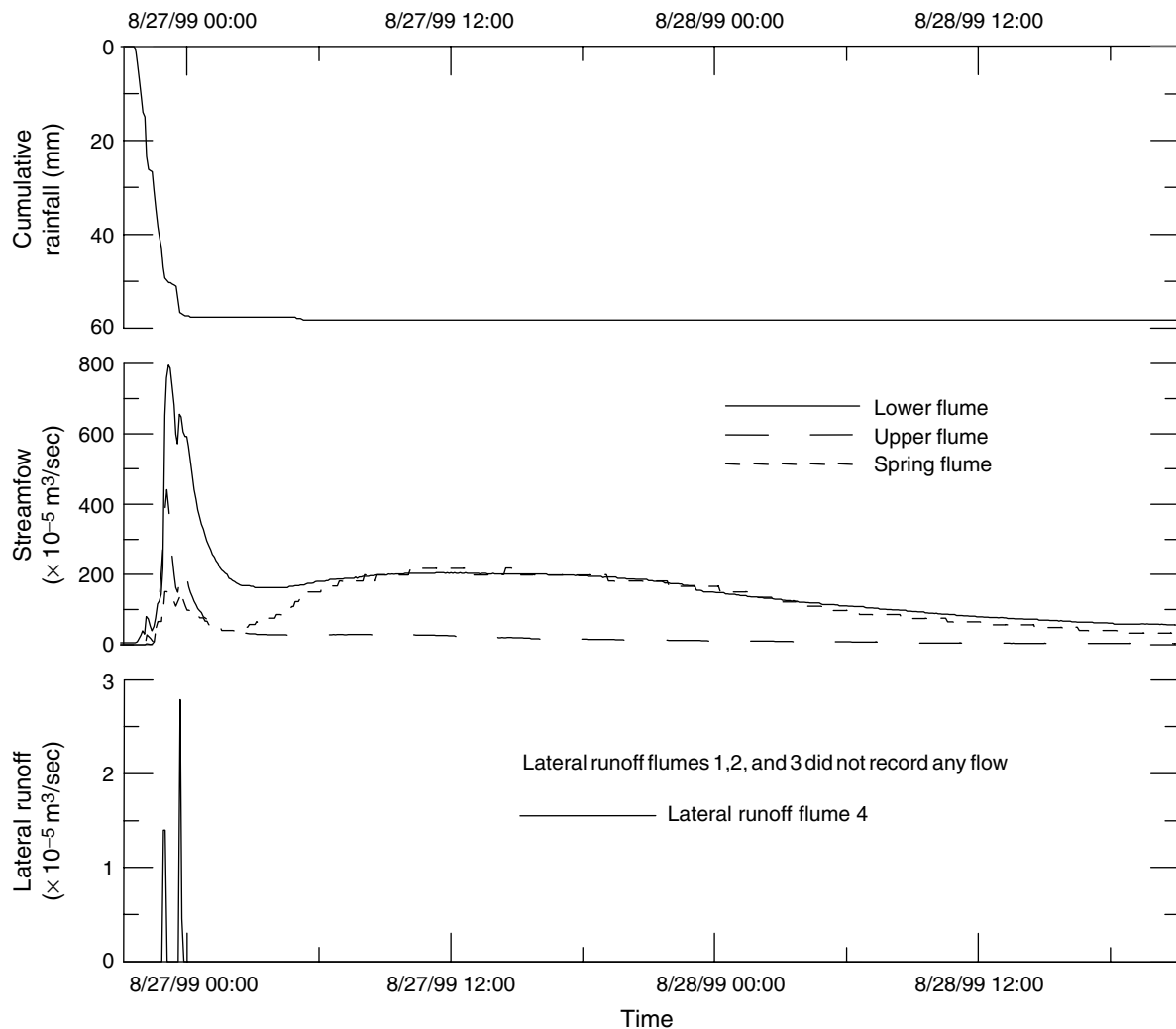


Figure 4. Rainfall and flow responses for periods before, during and after rainfall event 1 (August 1999)

(compare Figures 7 and 8). At 2215 hours on August 26 during rainfall event 1 (Figure 8b), the 5-min rainfall intensity was 2.8 mm. A total of 26.2 mm of rainfall had been received by 2215 hours. The IE surface runoff source area at 2215 hours was 240 m². Five minutes later, at 2220 hours (Figure 8c), the 5-min rainfall amount was 0.3 mm, and SRSs decreased from 240 to 140 m². Between 2215 and 2220 hours, the water table status remained almost the same (compare Figure 8b and c).

Surface saturation areas versus surface runoff source areas

Earlier runoff field studies (e.g. Rogowski, 1974; Anderson and Burt, 1978; Gburek and Zollweg, in press) assumed that rainfall input on SSAs produced surface runoff. The SSAs and SRSs delineated for rainfall events 1 and 2 were analysed to find evidence for this assumption. During rainfall event 1 at 2340 hours (Figure 6c), SSAs were recorded adjacent to lateral runoff flumes 1, 2 and 3, yet no flow was recorded in these three lateral runoff flumes. The rainfall (1.1 mm) that occurred between 2340 hours (August 26) and 0015 hours (August 27) did not produce any surface runoff.

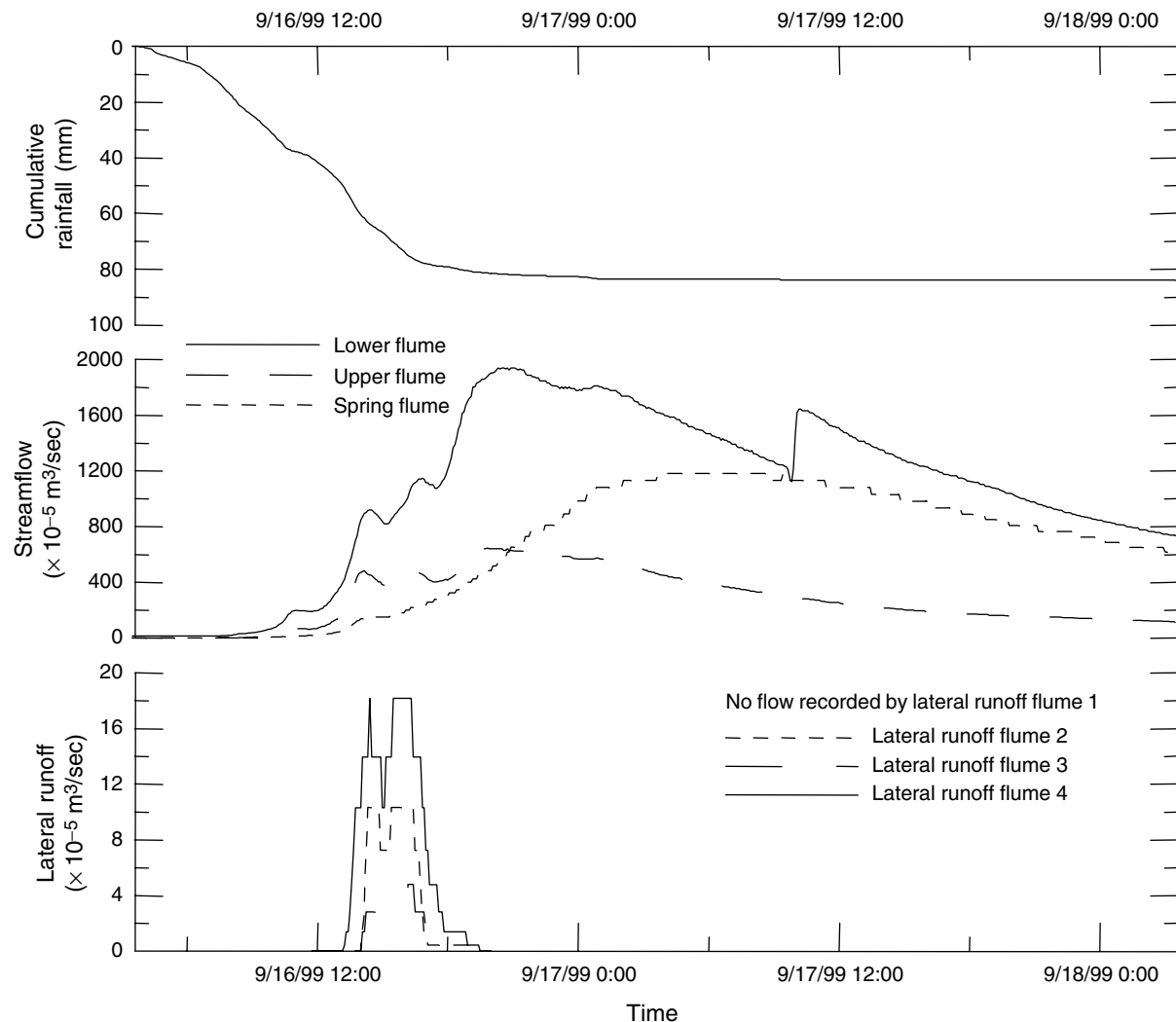


Figure 5. Rainfall and flow responses for periods before, during and after rainfall event 2 (September 1999)

Figure 8 illustrates the distribution of SSAs and SRSs (IE and SE) between 1410 and 1625 hours during rainfall event 2. The spatial and temporal distribution of IE and SE surface runoff areas varied markedly during the rainfall event. During this selected period, a total of 15 mm of rain fell, and if all SSAs produced surface runoff, the extents of SSAs and SRSs (SE) would have been equal, not counting the IE source areas. To the contrary, at 1625 hours (Figure 7d), the SSA was 225 m², whereas the SE surface runoff source area was 195 m². This shows that 30 m² of SSAs did not produce surface runoff at this time, although rain was still falling. Hence, simply measuring the water table status or the occurrence of surface runoff would not allow one to discern the 'true' dynamics of the hydrological response of the hillslope.

Interstorm dynamics

'When parts of the watershed are responding, the rest of the watershed could act as a reservoir that provides baseflow during non-rainy periods and to maintain the wet areas that will produce subsequent storm runoff' (Chorley, 1978, p. 29). Analysis of continuous data recorded by the SS and SR sensors for periods after rainfall

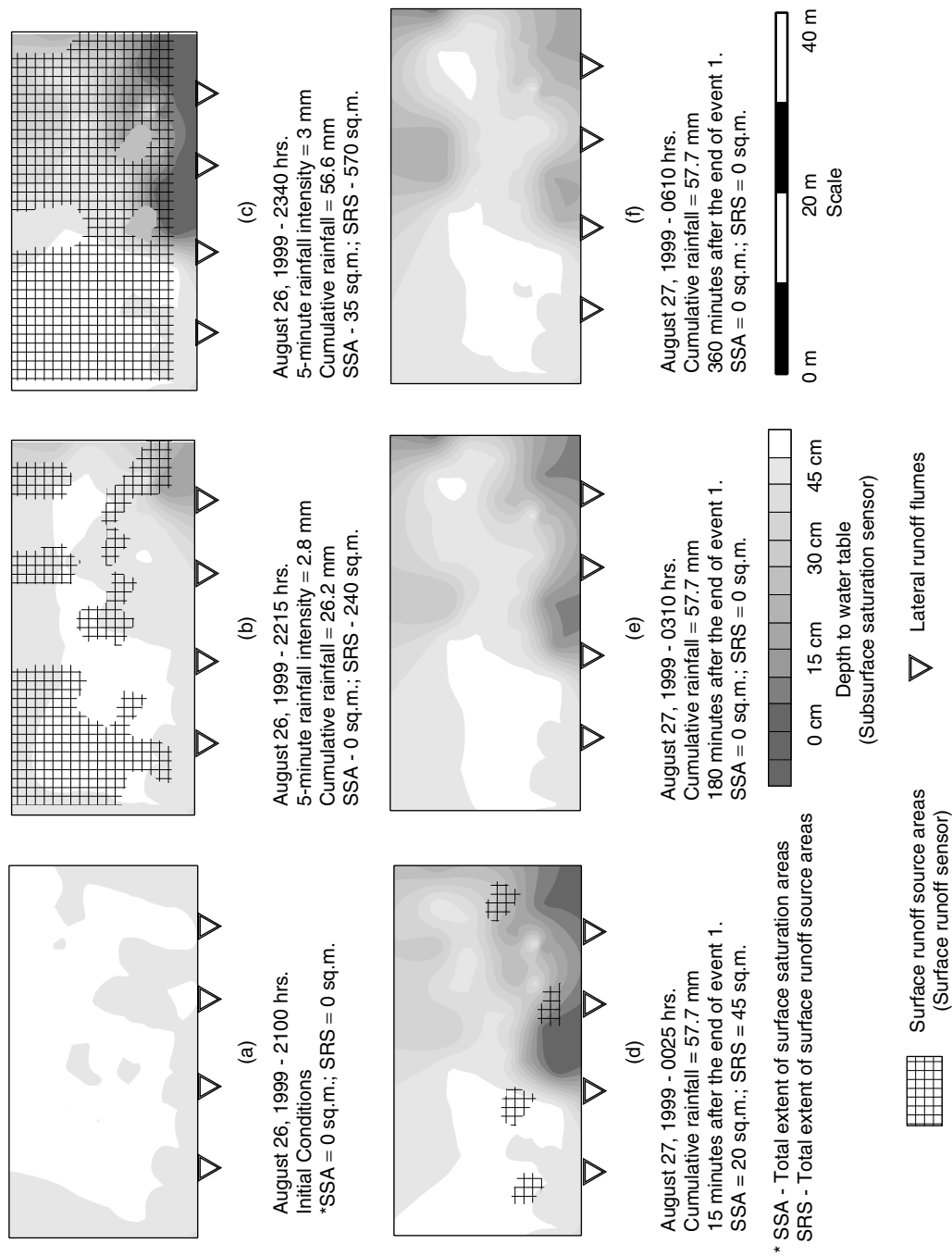


Figure 6. Dynamics of the study site hillslope before, during and after rainfall event 1 (August 1999)

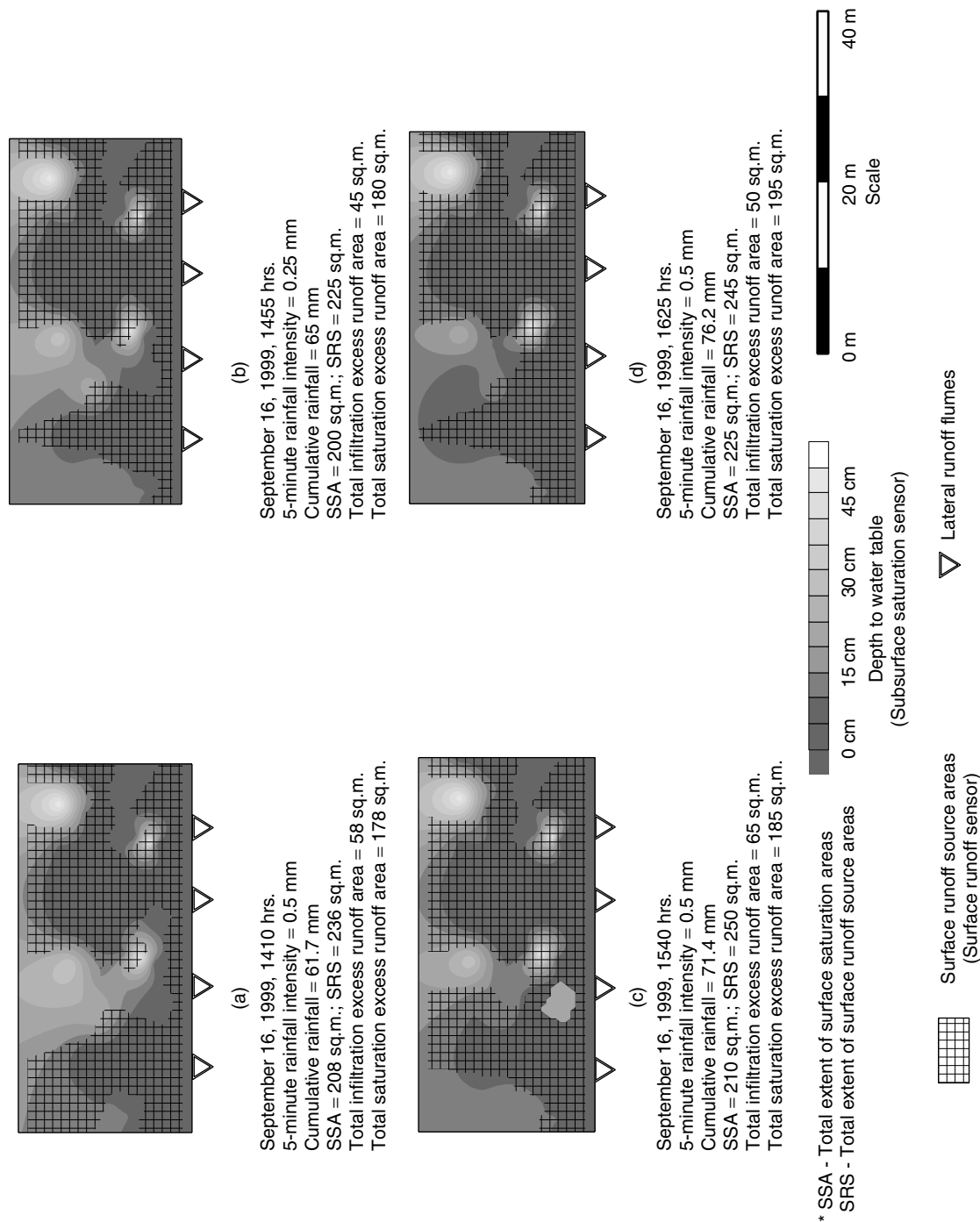


Figure 7. Rainfall data and hillslope dynamics for the selected period from 1410 to 1625 hours on 16 September 1999, for rainfall event 2

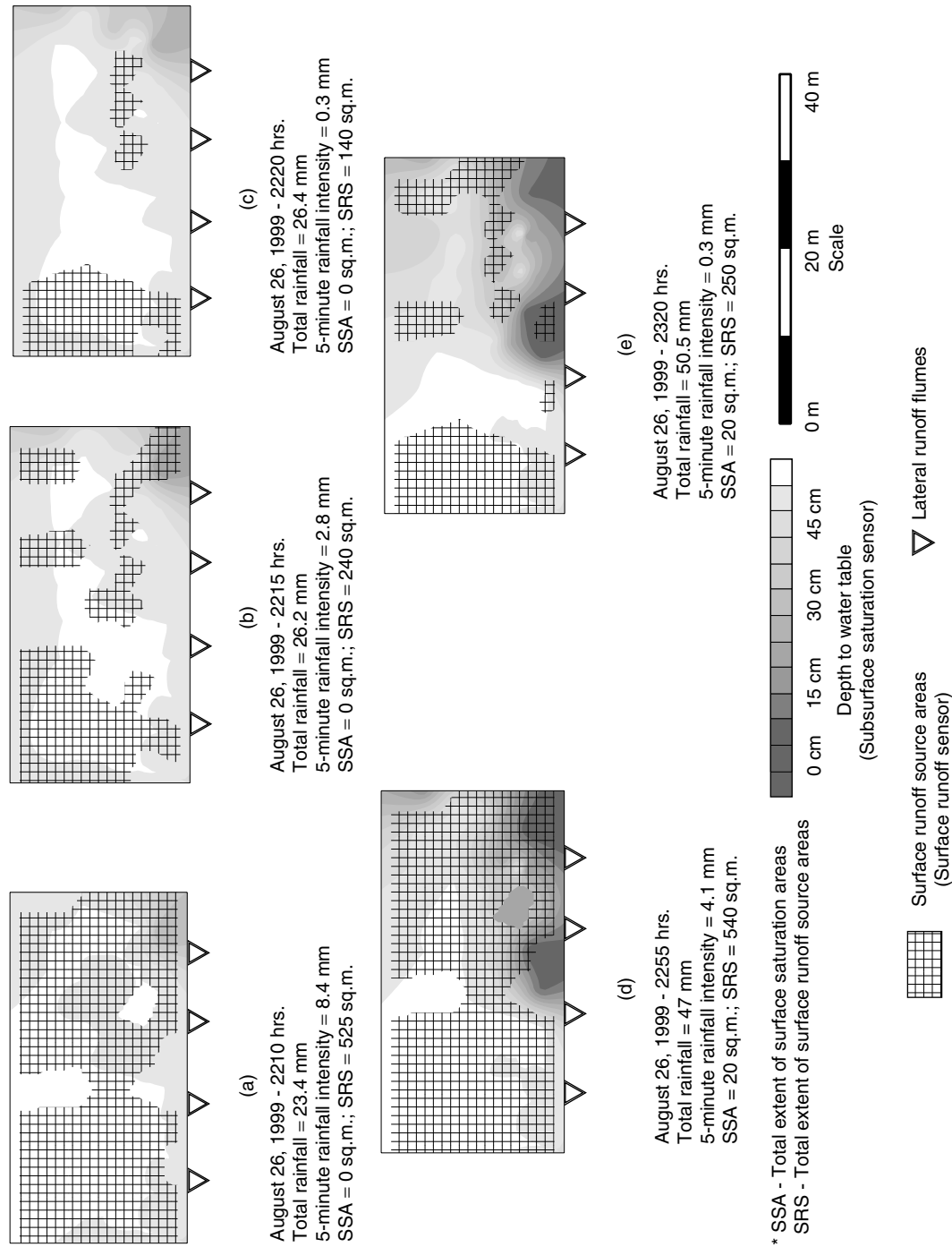


Figure 8. Rainfall data and dynamics of surface runoff source areas for rainfall event 1 (August, 1999)

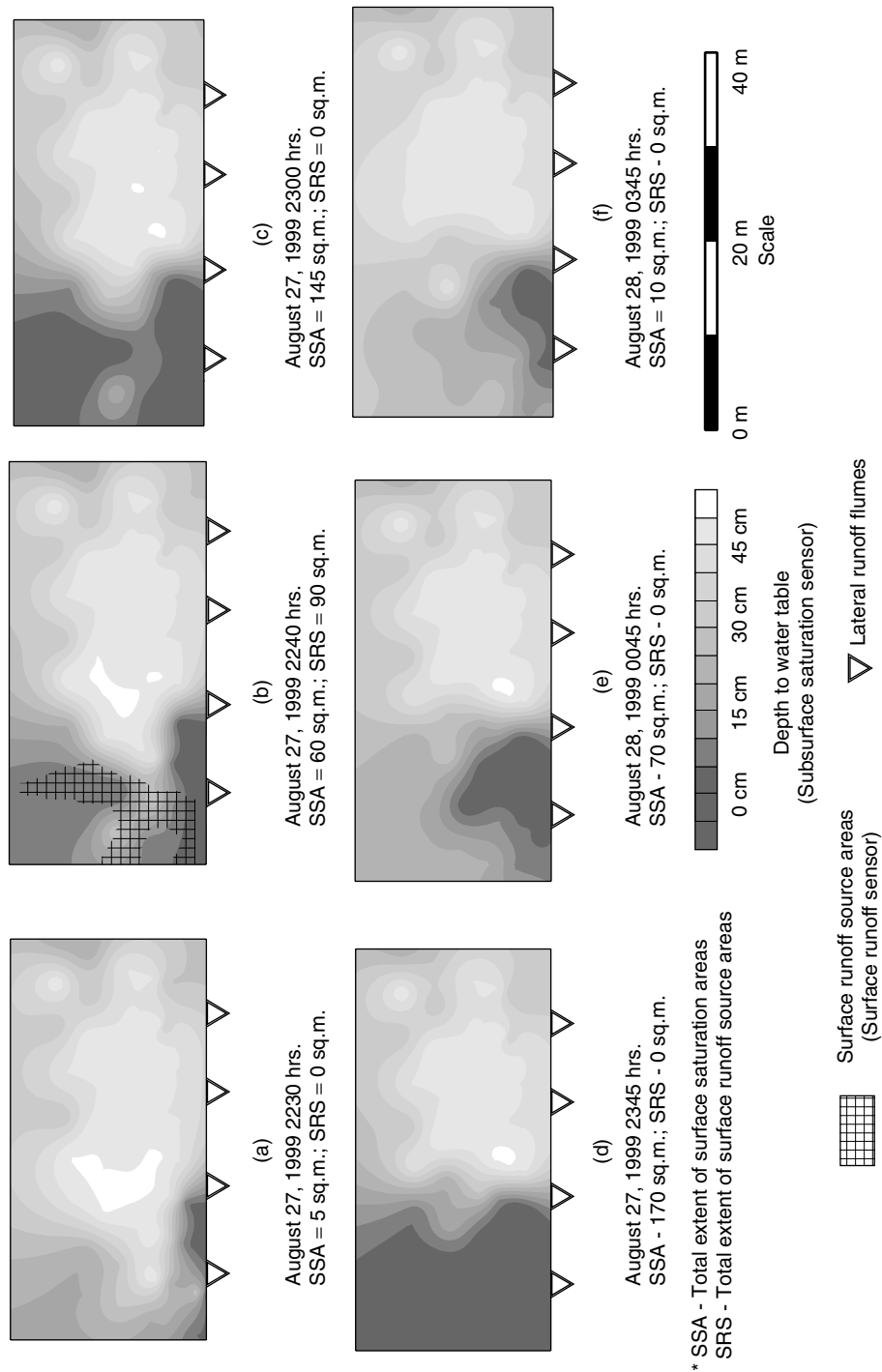


Figure 9. Subsurface drainage dynamics data recorded for a 4 h and 45 min time period that occurred approximately 24 h after the end of rainfall of rainfall event 1 (August 1999)

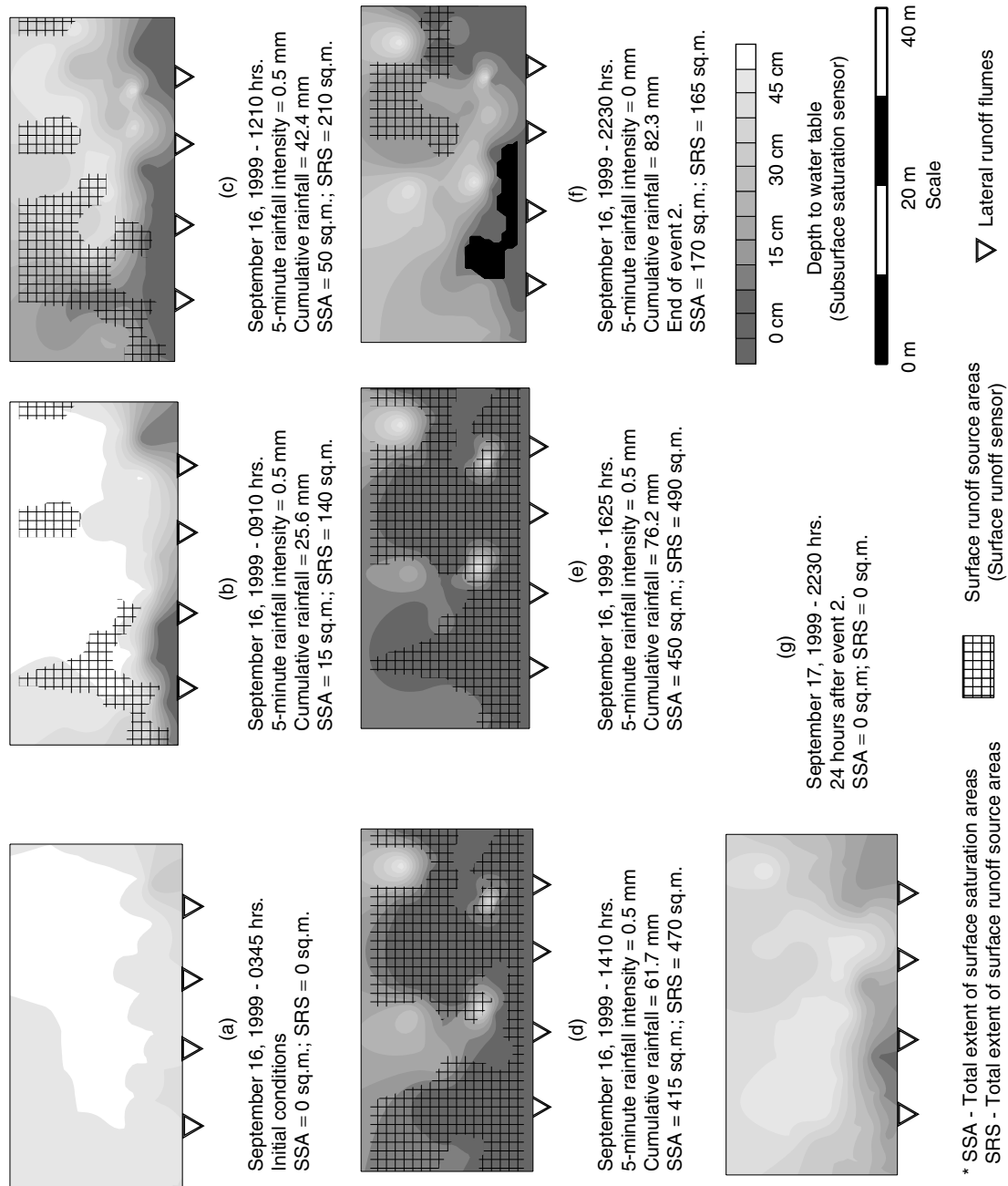


Figure 10. Dynamics of the study site hillslope before, during and after rainfall event 2 (September 1999)

events showed that dynamic subsurface flow processes occur between rainfall events. Simply assessing the conditions of a watershed at the end of a rainfall event does not necessarily provide a complete representation of the dynamics related to hydrological conditions.

Stream flow conditions before the start of rainfall events 1 and 2 were comparable (Figures 4 and 5). However, the surface and subsurface flow processes showed varying responses (in time and space) during these two rainfall events. During rainfall event 1, the dynamics of surface runoff flow processes were more readily observable than were the subsurface flow processes. Figures 6 and 8 and Figure 9 illustrate the spatial and temporal dynamics of the hillslope during the 'wetting' and 'drying' phases, respectively, of rainfall event 1. Figure 9 shows a series of plots depicting the water table conditions of the hillslope over 5 h beginning approximately 24 h after rainfall had ended for rainfall event 1. At 0610 hours on August 27 (Figure 6f, six hours after rainfall ended), no SSA was recorded. Following these conditions, one would expect the hillslope to continue the receding trend of the water table. However, at 2230 hours on August 27 (Figure 9a), SS sensors on the western side of the hillslope showed movement of the water table toward the surface. The rise of the water table to the surface and the occurrence of surface runoff during non-rainy periods is termed 'subsurface drainage'. At 2240 hours, disjunct subsurface drainage areas were recorded on the western side of the hillslope (Figure 9b). These SSAs expanded, and a maximum extent of 170 m² was recorded at 2345 hours on August 27; approximately 24 h after rainfall event 1 had ended. However, except at 2240 hours on August 27, no surface runoff from these SSAs was observed. Stream flow conditions during this period showed that most of the flow came from the spring flume (Figure 4), and none of the four lateral runoff flumes recorded flow. At 2240 hours, the lower and spring flumes recorded instantaneous flows of 170×10^{-5} and 165×10^{-5} m³/s, respectively. Thus, the spring flow constituted more than 95% of the flow volumes recorded at the lower flume during these periods. This spring flow contribution represents the dominance of subsurface flow processes during these periods.

Rainfall event 1 was a high-intensity, short-duration event, and subsurface flow processes took approximately 24 h to respond to this event. No literature references are available about these lag times for the subsurface flow processes after IE surface runoff events. For rainfall event 2, on the other hand, the response times for surface and subsurface flow processes were coincident. This can be seen in Figures 7 and 10, where the dynamics of SSAs and SE and IE runoff source areas are shown during rainfall event 2.

Advantages of the new sensors

The approach defined in this study eliminates the simplifying assumption that all SSAs produce surface runoff. Using two independent sensors, which can be paired, the SSAs and SRSs can be mapped independently. The uniqueness of the current approach as compared with the earlier approaches presented by Rogowski *et al.* (1974), Anderson and Burt (1978), and Gburek and Zollweg (in press) are:

1. the concurrent delineation of SSAs and SRSs (IE and SE);
2. the ability to describe the hillslope dynamics as a function of rainfall dynamics by measuring the hillslope dynamics at the same time-scale as the rainfall measurements;
3. the ability to measure the hillslope dynamics during periods between the rainfall events;
4. the ability to differentiate IE and SE rainfall events and identify the timings of surface and subsurface flow processes.

CONCLUSIONS

A hillslope-scale runoff dynamics study was conducted using newly designed subsurface saturation and surface runoff sensors. The dynamics (spatial and temporal) of surface saturation and surface runoff source areas were presented for two rainfall events from 1999 (August 26 and 27 and September 16). The August event (rainfall event 1) was a high-intensity, short-duration rainfall event as compared with the September event (rainfall

event 2). Although surface saturation was recorded over a small area (35 m²) within the study site during rainfall event 1, all the surface runoff from the study site came primarily from IE surface runoff. Conversely, rainfall event 2 produced surface runoff from both IE and SE surface runoff processes. The maximum extent of SRS recorded was smaller during rainfall event 2 (490 m²) as compared with rainfall event 1 (570 m²). The IE surface runoff source areas were spatially distributed during rainfall events 1 and 2 and were not necessarily related to the spatial occurrence of SSAs.

During rainfall events 1 and 2, not all SSAs produced surface runoff. The approach of using paired, independent SS and SR sensors helped to delineate SSAs that produced surface runoff from those that did not produce surface runoff. The approach to data collection and the instrumentation implemented in this study allowed a comprehensive monitoring of the hillslope dynamics as compared with earlier approaches described by Rogowski *et al.* (1974), Anderson and Burt (1978) and Gburek and Zollweg (in press).

Approximately 24 h (lag time) after rainfall event 1 had ended, subsurface water movement towards the surface was observed on parts of the hillslope (subsurface drainage to the surface), and for a period of 4 h the water table remained at the surface (SSAs) over an area of 170 m² within the study site. This highlights the importance of recording the watershed dynamics for periods between rainfall events. Further research needs to be done in establishing this lag time of subsurface flow processes after rainfall events.

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